APPLICATION OF INPUT CONTROLLING MECHANISMS TO STRUCTURAL DESIGN OF A TALL BUILDING

by

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SYNOPSIS

A structural design process of a two hundred-meter high building being constructed at a sub-centre of Tokyo is described. Special considerations are given in the design so that it may behave well against earthquake excitations;plans symmetric with respect to both axes surrounded by relatively rigid frames are adopted to avoid torsional vibration, the lower stories have wider floor areas than upper ones to prevent big axial stresses caused by vertical and horizontal loads, brace-system(wall system)is applied to effective use of materials, the horizontal expansions combined with multiple columns system are considered and a kind of damper is invented.

INTRODUCTION

Japanese Building Code was revised in 1963, and the height limitation disappeared. Since then more than one hundred buildings taller than forty five meters have been designed and constructed. The total number of the construction projects submitted to the Building Centre by now(at the end of 1972)is arround two hundred, and the tallest is about two hundred twenty meter high.

Therefore experiences of almost ten years in design and construction of tall buildings have been accumulated, but there still remain plenty of problems even only in the field of structural design. An example is the design load. No sufficient records have been obtained concerning the earthquake force. Consequently, the design process of the tall building has not been changed much from the early stage of ten years;earthquakeground motions recorded in U.S.A. are still used, though it has become clear that the mechanisms of earthquakes and the ground conditions are quite different in Japan.

In the construction of Yasuda-Kasai Main Office Bldg., which authors have participated and been in charge of structural design, a more rational design process with structural methods to control

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input earthquake forces has been analyzed. It is to be built in an area of Shinjuku-Ward, a sub-centre of Tokyo, where several tall buildings of two hundred meters high are planned to be constructed, (one is completed and a few are under construction). Yasuda-Kasai Bldg. will be completed by 1975.

At the early stage, a small committe was formed with structural engineers, designers, facility-planners etc. to exchange their opinions, and preliminary investigations of the site was started. Three conditions were imposed to the design; ratio of the total floor area to the site area(should be less than 1000%) and bias lines to keep sun light in the city are fixed from the city regulation, and the minimum height required from the building owner was two hundred meters.

In the design of tall buildings, structural engineers have the priority to some extent, and troubles with designers are much less than the usual case. The symmetric plans were accepted, and opinions of the structural engineers and designers accorded in the adoption of wider floor areas in lower storeys. It was preferable for structural engineers to decrease axial stresses of the column, and, at the same, was convenient for designers to solve the complicated function problems near the foot of a big structure. During this stage of fundamental design, rough calculation concerning the size of the members, and the response of the structure through modal analysis based on velocity-constant-assumption were made for various types of structures. One yer after, the fundamental plans including structural details were completed. And a half year more was necessary to complete the detailed design and the drawings and calculation-sheets were submitted to the Building Centre, to get the check and the approval.

The most difficult part in structural design was to assure the safety and comfortability against wind and earthquake excitation. After several methods were checked, double column method was adopted with newly invented damping system in the fundamental plan, but in the detailed designs, two possibilities(double column system and PC wall system of Taisei Const. Comp. which was decided to be the main constructer of the building) are presented and now are compared from the economical view point.

PRELIMINARY INVESTIGATION

The preliminary investigations were carried out at the beginning stage of the fundamental design. As many data were available in that area, the constitutions of ground were known before the investigation to some extent. The boring was made at five places within the site, and soil tests were also carried out. The microtremor measurements were done at six different depths in the site and the final results were obtained in the form of the power spectra. The velocity of S and P waves was known, and density of soils was obtained from tests, and the stress-strain curve of the soils was made. In brief, the ground conditions are not bad; though there are soft layers of alluvium near the surface, a hard gravel layer which can sufficiently support the weight of the building is horizontally located at the depth of twenty meters. Water level is relatively low, and there might be no trouble to adopt open-cut system to take out the surface layers. (Method to dig has not been finally decided yet.)

DECISION OF THE SHAPE

The work to complete the fundamental design was started from the list up the necessary area of rooms and public spaces, with their preferable locations and connections as usual, then shapes of plans and elevations were roughly decided under the imposed three conditions plus the ground condition. The mat-foundation system was adopted because it was the most stable and rigid foundation, and base floors were to be used for the garage , machine rooms , stores, and water tanks. Then, several types of the buildings were checked(fig 4-1). The first type is not structurally desirable, because the axial forces produced by lateral forces become big. The second type is most widely used in Japan, though there is some stress concentration at the place where the floor area suddenly changes. The third type has no structural problems and may be the most general shape in the future, but at present, many materials and equipment should be specially ordered at each floor and the building cost might be expensive. The fourth type is also structurally good, but from the same reasons of the third type, the fifth type remains.

ANALYSIS OF STRUCTURAL METHODS

From such experience that some of flexible tall buildings vibrated with big amplitudes by distant earthquakes and frightened the people in them, the pure rigid-frame system disappeared from our plan, after the displacement response was checked. But if only a few frames of the whole structure have bracings, stresses are concentrated and it becomes difficult to anchor it to the ground. (If a structure is small and rigid, rocking motion is effective to decrease input earthquake force and to increase the damping.

But it is not desirable in tall buildings.)To distribute the lateral forces to frames, many braces are adopted at the first stage of the plan, but finally they are put at the machine rooms and central cores to form a "Hat" and "Cross" structure, and the bending deformation is predominant in the first mode of vibration. The outside columns of the lower floors so incline that most of the stresses produced in them may be axial ones. The angle of inclination is to some extent sensitive, as it sometimes makes a node-point in the lower storey in the first mode vibration.

Whether the wall is used instead of a bracing has not finally been decided yet, because the cost estimation is closely related to the decision. When the brace system is used, double column system with a horizontal expansion may be adopted to realize elastic non-linearity of the structure as shown in Fig. 5-1.

Such a height as two hundred meters contains a problem as the proportion of the plans determine the most effective lateral load to the building;the wind pressure or earthquake force. The design can be quite different if the wind pressure is the most effective. A rigid and not too light structure is preferable. The case of Yasuda-Kasai Bldg. the proportion of the plan is so designed that the design earthquake force is much bigger in the N-S direction, and slightly bigger in E-W direction.

The storeys upper than the fifth are of steel structure, lower than B-3 are of RC., and intermediate part is of SRC. It is desirable to haverigid and heavy foundations and base floors to minimize the relative lateral deformations within the structure, and plenty of seismic walls are installed at this low part of the building. The parts where the columns incline to support the axial force produced by lateral loads are connected to the thick surounding wall at the base, and there is no problem for the anchor. The braces in the N-S direction are located at the elevator shafts and the number of braced frames decrease as the number of the elevator decrease in the upper floors. There is a thick RC floor at the connection of steel frames and SRC frames to distribute the lateral stresses smoothly. Thanks to the shape, both of the wind pressure and earthquake force are about ten percents less than the case of the usual rectangular elevation.

DOUBLE COLUMNS AND DAMPER

The building structures easily take the energy through the dynamic excitation of similar frequencies of its own, and if the excitation contains components of various frequencies, it picks up the similar ones and becomes in a pseudo resonance state. So at the beginning of an earthquake, it vibrates in higher modes and produces

a big acceleration, then it shakes in the fundamental modes with big deformations because of non-stationary vibration of the earthquake. Therefore, if a structure has such a control system that it does not produce big accelerations against high frequency excitations, and does not get large deformations against low frequency excitations, then it is very preferable. One method to realize this state is to use some mechanisms to give elastic non-linearity to the structure, and another is to increase the damping of the structure to avoid sharp peak values. Elasto-plastic non-linearity usually used is sometimes not very desirable, as the periods of the structure become longer just at the time when the excitation of low frequencies is predominant.

The "Double Columns System" or "Multi-Columns System" is one of those methods to produce elastic non-linearity in a building. As shown in Fig. 6-1, doubled or trippled columns are used where inner columns only support the axial and bending stress, and when the deformations are getting large, the outer columns also share the stress, thus hardening spring type stiffness can be obtained Fig. 6-2. The characteristics can be adjusted through the gaps between inner and outer columns, and if the excitation has similar characteristics to those of El Centro and Taft earthquakes, around four-centimeter clearance is usually quite sufficient. The system uses horizontal expansion joint and a kind of damper. It is planned to be installed at the ground floor through three storeys of Yasuda-Kasai Bldg. in its fundamental design. Because of the system, the upper part can be designed to be very rigid, and there is no problem when the secondary structural elements are fixed to the main ones, otherwise secondary elements should be so designed that can follow the deformation without big resistance.

Double or Multi-Columns System shows many advantages when a structure is rigid and built on the good ground. Though Yasuda-Kasai Bldg. is very rigid when compared with usual ones of the same height, still it has the fundamental natural period of longer than three seconds and is flexible. (The bigger part of the deformations is taken by the bending ones.) Now adoption of the system depends on the cost estimation in the detailed design. Though it is necessary to replace to new ones after big earthquakes, another possibility is installation of PC walls with flexible joints.

Damper adopted for the Double Columns System is a "break type", small blocks of concrete (sometimes of wire-concrete) are put in the expansion, and when they are crashed to small pieces other blocks drop into the gap and absorb the energy during the movement of the building. This is a kind of "intended" breakable parts, and some of the energy given to the structure is absorbed,

and save other parts from damage(Fig. 6-3).

STRUCTURAL DESIGN STEPS

There is a routine process in structural design of tall buildings in Japan, such as

1) Preliminary investigation of the site(like what described in previous pages.)
2) Determination of fundamental design after discussions with the designer.
3) Estimation of fundamental natural period through empirical formula.
4) Estimation of the weight at each storey.
5) Calculation of storey- shear coefficients or design lateral forces for elastic analysis through recommended formula of AIJ[I], BRI[II] and so on.
6) Determination of the materials(for example grades of steel) and dimensions of structural members.(stresses and deformations are checked)
7) If necessary, recalculate storey-weight.
8) Calculation of eigen-values and eigen-vectors.
9) Elastic response calculation to recorded earthquake such as El Centro, Taft, Tokyo 101 etc. putting their maximum value 150 - 300 gals.
10) Elasto-plastic response calculation to above mentioned earthquakes setting their maximum values to 300-500 gals and check whether the structure is stable or not.
11) If the results of calculation at any step is not preferable, adjust the size of member, and repeat the calculation until satisfactory results are obtained.

The similar steps have been taken in our design, but a process shown in the block diagram(Fig. 7-1) is also adopted to check the calculation. The difficulty was in the assumption of characteristics of motion at the bed rock(base rock). Because of the insufficiency of the data, very rough calculations like white-noise assumption were made, and Haskel's Transformer was combined. The constant values of the ground are taken from the data obtained at preliminary investigations except the assumed value of damping. The properties of the artificial waves are similar to those obtained from micro-tremor measurement at the corresponding layers. The response of the building to artificial earthquakes thus produced is much smaller than that to recorded earthquakes like El Centro

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40 NS. It is quite natural, because the data are obtained under the condition of very small deformation. So adjustment of the constant values were made, taking into account the soil-test data, but the response results were a little smaller than those by El Centro. The deformation of the bed rock itself is not clear, and the constitution of the deep ground is usually not known. Consequently, the shown block diagram can not fully be traced at present, unless rough assumptions are adopted.[I] For medium size earthquakes, statistic data are available in Japan, where earthquakes are most frequently observed. For very severe earthquakes, still the estimation of the properties of the earthquake is quite difficult. The earthquakes in japan are said to contain long-period wave components in comparison with those in USA, but records of really big earthquakes have not sufficiently been obtained. (Niigata Earthquake in 1964 should be put into an exceptional case because of the liquifaction of the ground). This feature can be seen in the data obtained at Hatchinoe in 1968 in Tokachi-Oki Earthquake, and after shock records(1924) of Great Kanto Earthquake in 1923. (After shock records might have much different characteristics from those of main shock as the size of the moved blocks are very different.)

Linear stochastic process is adopted as shown in the block diagram, an safety of more than 90% are assured against the artificial earthquakes with mean square value of 200 gals at the ground surface. (This corresponds to the max. value of about 600 gals at the surface and around 200 gals at the founded layer.) As for the non-linear stochastic process, trial calculations are made based on the probability density to pass an area and the corresponding damage level estimated through energy calculation. But this method still require more data than available ones.

CONCLUSION

Many tall buildings have been constructed in earthquake countries. It seems however, there have been neither recommendable design process nor structural methods yet, which can certainly assure the safety of human lives against severe earthquakes. It is possible to produce such an artificial earthquake records with a reasonable value of the maximum acceleration that can crash the tall building in the computer. Seismologists suggest the possibility of big ground movements of low frequencies resulted with a big fault, and if so, it is no more a problem within the computer. When a building is low and ductile, man can escape even from the collapsing structure like the case of Hakodate Univ. in 1968 Tokachi-Oki

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I There is a five year big project of Japanese Government to clarify the ground and bed rock motion.

Earthquake. But no collapse is allowed for a tall building.

It is not very difficult to control the earthquake effect through some mechanisms and with the non-linearity of the soils when a structure is low and rigid. But the only privelege of tall buildings is that their foundations are usually set on deep and hard layers where the values of displacement and acceleration during an earthquake are much smaller than those near or on the ground surface.

Through the structural design of Yasuda-Kasai Bldg. we felt a big gap between the necessary data for engineers and available ones given from seismologists. The building will be able to survive severe earthquakes of less than one hundred years interval, which will take place for sure during the usable life of the building, but no data can be used for the design against such an earthquake caused by the movement of big crustal or mantle block near Tokyo, once in three to five hundred years. Beliving in a seismologist's words that "no such an earthquake for many years more", we except the progress of "earthquake prediction".

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